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PERSONAL THEATER OPTICAL SYSTEM

FIELD OF INVENTION

The present invention relates to light and image projectors and particularly those for projection video images.

PRIOR ART

In the prior art there are various light sources and image projectors. The simplest light projector comprises a flashlight and a more complex device comprises an image projector with an incandescent light source such as in U.S. Patent No. 6,227,669. However, these prior art projectors have significant disadvantages in that they either heavy, complex, dim, comprise a great number of expensive parts, too large, generate too much heat, require cooling fans, make too much noise and have short bulb life.

BRIEF DISCRIPTION OF THE DRAWINGS

Figure 1 illustrates the basic system layout of the optical system of the present invention;

Figure 2 illustrates the Optical System Telecentricity used in the present invention;

Figure 3 illustrates the Optical System of the present invention using Double Telecentricity;

Figures 4A and 4B illustrates the Red Compound Hyperbolic Emitter (CHE) used in the present invention;

Figures 5A and 5B illustrates the Green/Blue Quad Compound Hyperbolic Emitter (CHE) used in the present invention; and

Figure 6 illustrates a Dichroic X-Cube or DX-Cube used in the present invention.

DETAILED DISCRIPTION OF THE INVENTION

As show in Figure 1 the optical system of the present invention is a solid-state front projector consisting of an illumination subsystem and a projection subsystem. The illumination subsystem illuminates a single Microvue liquid crystal on silicon (LCOS) microdisplay with light from red, green, and blue light emitting diodes (LEDs). The projection subsystem images the LCOS microdisplay to a reflective viewing screen. Gray scale and color are created by temporally dithering the LCOS microdisplay in conjunction with the LEDs. SXGA resolution at 24-bit color and 60Hz frame rate are achievable with this system.

Illumination Subsystem

General Illumination System Description

The illumination subsystem is a critical or Abbe illumination system that images red, green, and blue (RGB) LED sources to the LCOS microdisplay. The designed illumination system, in addition to being a critical illumination system, is doubly telecentric. The double telecentricity is an important characteristic that optimizes light processing by the LCOS microdisplay while accommodating the configuration of the LEDs.

A telecentric optical system is one where the aperture stop is located at a focal point of the optical system causing either the entrance pupil or the exit pupil to be located at infinity. The aperture stop is the physical stop that limits the amount of light that propagates through the optical system. The entrance pupil is the

image of the aperture stop formed by all active optical elements preceding the aperture stop. The exit pupil is the image of the aperture stop formed by all active optical elements following the aperture stop. An optical system exhibiting object-space telecentricity has its aperture stop located at the rear focal point of the optical system. The entrance pupil is therefore at infinity in the object space in a space, a space so called because it is where the object is normally located. An incident chief ray propagating from an object point parallel to the optical axis will travel through the center of the aperture stop to the image plane. The chief ray, by definition, is the ray from an object point that propagates through the center of the aperture stop and hence the entrance and exit pupils since they are images of the aperture stop. A chief ray from another object point will do the same. If the object points are shifted then the resulting image point magnifications do not change and the points are only blurred in the image plane. Figure 2 illustrates the concepts of telecentricity. Similarly, an optical system exhibiting image-space telecentricity has its aperture stop located at the front focal point of the optical system. The exit pupil is therefore at infinity in a space where the image is normally located. An incident chief ray propagating from an object point will travel through the center of the aperture stop exiting parallel to the optical axis at the image plane. A chief ray from another object point will do the same. If the image plane is now shifted then the resulting image points magnification do not change and the points are only blurred in the image plane. A doubly telecentric system combines both of these features as illustrated in Figure 3.

The LCOS microdisplays use ferroelectric liquid crystal technology to switch the state of polarization of the incident light in the plane of the cell. However, the effectiveness of the microdisplay's polarization retardation and associated state switching is a function of the path length of the light in the ferroelectric material. In other words, the microdisplay operates best when light is normally incident on its active plane and all the rays of light travel nearly the same optical path length in the ferroelectric material. Although the microdisplay can accept up to a 25 degree off axis beam (f/1.2) it performs best and produces best contrast at f/3 or approximately a 10-degree maximum incident angle. However, in a typical illumination system it is not uncommon to have f-numbers very close to f/1 in order to maximize the amount of light illuminating the object. Larger f-numbers transmit less light. The chief ray at the edge of the source in such a system enters the microdisplay at a large angle and will be switched significantly differently than an on-axis ray from the center of the source. Therefore, it is advantageous to send light into the LCOS microdisplay at near normal incidence from all points of the source. An illumination subsystem that provides image-space telecentricity at the LCOS microdisplay forces the chief ray from each LED to illuminate the microdisplay perpendicular to its plane. The chief ray in this case is the ray of light from the center of each LED that propagates through the center of the aperture stop. Therefore, light incident across the microdisplay aperture more uniformly propagates through the ferroelectric material, especially the chief rays resulting in a more uniform distribution of light from the microdisplay. Although the bundle of light around the

chief ray will experience larger path lengths through the ferroelectric material, the majority of light from a particular source point will be much closer to optimum conditions than a non-telecentric system operating at a similar f-number.

LEDs typically are arranged on an electrical board with their emission axis perpendicular to the board. Such a source is considered a telecentric source and suggests using a telecentric optical system for imaging purposes. In this case the optical system would have object-space telecentricity. An illumination subsystem that provides object-space telecentricity at the LEDs forces the chief ray from each LED to emit parallel to the optical axis of the LED. In other words a ray emitting from the center of the LED parallel to the optical axis is forced to be the chief ray.

The illumination system utilizes both object and image space telecentricities to accommodate the requirements of the microdisplay and inherent LED layout. Figure 3 illustrates the doubly telecentric operation of the projector. The illumination system uses plastic, aspheric, Fresnel condenser lenses to image the sources to the microdisplay. The current system uses three such lenses, whose Fresnel side is adjusted to minimize illumination system aberrations. Standard glass lenses could also be used as well. However, it is easier to manufacture larger aperture, lower f/number Fresnel lenses than equivalent glass ones. Furthermore, the Fresnel lenses are easily asphherized to correct for spherical aberration, thin, lightweight, and less expensive than glass condenser lenses.

Illumination System Light Sources

The heart of the illumination subsystem is a solid state source of red, green, and blue LEDs. Currently, 9 of each color of Lumiled's Luxeon 1W red (44lm) and 5W green (120lm) and blue (30lm) LEDs are used as sources. The LEDs are arranged in a 3x3 array. The 1W red LEDs are a 1mm x 1mm die encapsulated in silicon with a 5.6mm hemispherical dome. The 5W green and blue LEDs are actually 4 1mm x 1mm die arranged in a 2 x 2 die matrix. The total size of the green and blue LED die are 2mm x 2mm. These LEDs too have their die encapsulated in silicon with a 5.6mm hemispherical dome. All of the LEDs emit with a hemispherical Lambertian emission pattern. A Lambertian emission pattern emits with equal brightness in all directions around the hemisphere while exhibiting a cosine fall off in intensity and irradiance as a function of angle from the normal of the emission surface.

A fundamental problem of using such LEDs is capturing the available light from the LEDs and concentrating it into an area and emission angle that can efficiently and physically be imaged by the critical illumination system to the microdisplay. The hemispherical dome lenses are large and limit the collection and ultimately the concentration of the light from the LEDs on the microdisplay. The theoretical thermo-dynamic limit of light concentration is called the conservation of brightness or throughput or etendue. It is the product of the emission area of the source and its emission solid angle and is conserved as light propagates through the optical system. Small area sources with large emission solid angles cannot be forced, for example, into narrow emission solid angles with the same emission area.

Compound hyperbolic concentrators (CHCs) where used to optimize the collection efficiency of light off of the LEDs. Compound hyperbolic concentrators and their more common relative, compound parabolic concentrators (CPCs) were originally developed as solar concentrator technologies concentrating solar energy to a detector. When used in reverse, i.e. LED replacing the detector, they become highly efficient illuminators or emitters. As such they will be referred to hereafter as compound hyperbolic emitters (CHEs). The CHEs were designed as total internal reflecting (TIR) CHEs that fit over the actual LED die with the hemispherical lens removed from the original LED package. The surface of the CHE is designed to reflect light by total internal reflection. The cavity at the bottom of the CHE is filled with an index- matched encapsulent, which couples light from the die directly to the CHE.

The red CHEs are different from the green and blue CHEs. This is due to the difference in size of the red die verses the green and blue die, which each have the same size but larger than the red die. Furthermore, the red CHEs are truncated in length to limit their output apertures to accommodate magnifying their output to the microdisplay. The non-truncated output aperture size is directly related to the input aperture size by the following equation.

$$\text{CHE Output Radius} = \frac{\text{CHE Refractive Index} \times \text{CHE Input Radius}}{\text{Sin}(\text{CHE Angle})}$$

The truncation only limits the theoretical emission efficiency to 90%. This number has been verified

empirically. The red CHEs are symmetric in shape. A red CHE is illustrated in Figure 4.

The green and blue CHEs have bilateral symmetry. The green and blue CHEs are actual a "quad" CHE composed of four separate CHEs. The green and blue dies are twice as large as the red die and in fact are made of four individual 1mm x 1mm die. Placing a single CHE over the larger green and blue die produces an excessively large CHE output size that is ultimately inconsistent with that required to image light from the CHEs to the microdisplay. The quad CHE was created to reduce the CHE output size while still maintaining reasonable emission efficiency. The quad CHE consists of four individual CHEs centered on each of the four die of the green and blue LEDs. The surfaces of adjacent CHEs trim each other along planes centered on the quad CHE. Figure 5 illustrates the quad CHE.

These devices must also be truncated and the truncation and trimming limits the theoretical emission efficiency to 65%, which also has been verified empirically.

<u>DX (Color) Cube</u>

Light from the red, green, and blue (RGB) LEDs has to be recombined before it is processed by the microdisplay in the optical system. Color cubes and dichroic filters are commonly used for color recombination and splitting and in tri-color liquid crystal display (LCD) projection systems. The color cube, sometimes called an "X-cube" is essentially a dichroic beam splitter composed of four glass prisms coated with special coatings along the prism sides but not the prism's hypotenuse. When the prisms are glued together

their sides form the coated diagonals of the cube and hence the name X-cube. They are typically located very close to the LCD and hence are required to be of a high optical quality. The major drawbacks to color cubes are their cost, size and weight.

Dichroic filters are used to split light from a polychromatic (white) source, typically a discharge lamp, into component red, green, and blue (RGB) colors. They are typically located at the source end of the illumination system. The separate colors, after processing, are then recombined by the color cube. The major draw back to dichroic filters is their poorer optical quality as compared to color cubes and the fact that they split two colors and not three at a time.

A dichroic X-cube, the DX-cube, was created for the optical system to recombine the RGB LED light before it is processed by the microdisplay. It is made by cutting either a red or blue dichroic filter in half. The end of each half is then secured to the middle of the other filter, forming another "X" but with thin, glass plate dichroic filters. Hence the name dichroic X-cube or DX-cube for short. The dichroic filters need not be of high optical quality since they are located in the illumination end of the optical system. The obscuration created by the joint between the halves is small and furthermore is not in a conjugate plane to the microdisplay. This and a homogenization component located elsewhere within the optical system mitigate any non-uniformity created by this seam. The DX-cube is illustrated in Figure 6.

Fold Mirror

A fold mirror is included in the illumination system to fold the optical path to make a more compact system. It is a front surface, enhanced-aluminum coated to minimize reflective loss.

Diffuser

A diffuser is place just before the third Fresnel condenser lens. The diffuser homogenizes or makes uniform any non-uniformity from the RGB LED sources. The particular diffuser used in this design is a Physical Optics Corporation (POC) Holographic Light Shaping Diffuser (LSD). Plastic or ground glass diffusers could be used as well but the POC material has much higher transmission efficiency than those other devices.

The diffuser's position in the optical system is critical for optimum homogenization of the light reaching the microdisplay. Placing the diffuser at the ends of the CHEs, for example, a conjugate position of the critical illumination system, does not provide for the best uniformity. A position closest to the last optical element in object space, on the object space side of the element, provides optimum homogenization in this particular design.

Polarizing Beam Splitter

Light from the RGB LED sources is non-polarized or natural polarized. However, light incident on the LCOS microdisplay must be linear polarized. Furthermore, the LCOS microdisplay is a reflective and not transmissive device. A polarization beam splitter is used to linearly polarize the light entering the microdisplay and then

reflect the orthogonally polarized component from the microdisplay into the projection lens.

The current polarizing beam splitter is a wire grid type made by Moxtek. Other types of polarizers could be used, such as a beam splitter or cube beams splitter with a polarization coating. However, the wire grid type is thin, lightweight, relatively inexpensive, and does not introduce a significant, additional glass thickness into the illumination or the projection optical path. Furthermore, the wire grid polarizer generally accepts smaller f/number beams (larger or wider acceptance angles), have high extinction ratios, and higher transmission and reflection of linearly polarized light than the typical polarization beam splitters.

LCOS Microdisplay

The microdisplay is an SXGA color reflection mode Liquid Crystal Display (LCD) capable of displaying full color computer or video graphics with a spatial resolution of 1280 x 1024 pixels in an active area of 17.43mm x 13.95mm. The liquid crystal on silicon (LCOS) device uses a ferroelectric, as opposed to twisted neumatic, structure to switch the state of incident polarization very rapidly. Gray scale and color are achieved by temporally dithering the LCOS microdisplay in conjunction with the LEDs.

Light Trap

The light trap is a light trapping box designed to suppress the orthogonally polarized non-signal light reflected from the polarizing beam splitter. This light, if not suppressed, will contribute to significant contrast

reduction if it is reflected or scattered back into the signal beam path.

The light trap is composed of an anti-reflection (AR) coated black-glass and a highly absorptive black wall. The AR coated black glass is oriented at 45 degrees with respect to the incident light. Most of the light is transmitted visible light that enters the AR coated black glass and is highly absorbed as it propagates through the absorptive material. The small portion of remaining reflected visible light propagates to the highly absorptive black painted wall. Any back scattered light is scattered to the AR coated black-glass where the majority of this small amount of light further absorbed by the absorptive glass. The trap cavity and associated aperture is designed to block a direct stray light path back to the microdisplay and the imaging path. Many orders of magnitude in stray light reduction are achievable with this arrangement. Additional folds can be added to further suppress any back-scattered component.

Projection Lens Subsystem

The projection lens images the microdisplay to the viewing screen. The projection lens is a nine element in six groups, f/1.75 lens. It is designed to project a 40-inch diagonal image at a distance of 8 feet. The projection lens also contains a wire-grid linear polarizer at the aperture stop position. The polarizer is needed to improve the contrast ratio of the signal after refection from the wire-grid beam splitter. The contrast ratio off of this component is typically only 20:1-50:1. The linear polarizer in this particular design is placed at the stop because this space occupies a minimum area and the angles

of incidence of the light are a minimum. The linear polarizer can be rotated independently of the lens barrel to accommodate contrast ratio changes as the lens is rotated to change focus.